Wang Y, Chen L, Jia B, Roskilly AP.

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Applied Energy 2017, 195, 93-99.

DOI link to article:

http://doi.org/10.1016/j.apenergy.2017.03.032

Date deposited:

28/03/2017

Embargo release date:

07 April 2018

Experimental study of the operation characteristics of an air-driven free-piston linear expander

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Abstract:

Free-piston engine is a kind of linear internal combustion engine, and shows advantages on simple mechanical structure, low frictional losses, high thermal efficiency and operational flexibility. In this research, an experimental test rig of a dual-piston air-driven free-piston linear expander (FPLE) is established using the FPE concept. A linear generator is used to convert the mechanical work of the pistons into electricity during the expansion process. The piston dynamics, the output voltage of the generator, and the expander operation frequency, as well as the system energy conversion efficiency are identified. It is observed that the piston displacement profile is similar with a sinusoidal wave. The piston is found to run at relative high speed during the middle stroke, and peak velocity is usually achieved when the piston approaches the middle stroke. The output voltage of the generator is sensitive with the piston velocity. With higher driven pressure, the expander frequency is higher. The energy conversion efficiency increases with higher driven pressure and can reach up to 55% with a driven pressure of 3.75 bar. This research presents a fundamental analysis of a FPLE prototype, which can be used as a guidance for the future design of this FPLE type.

Key words: Free-piston; linear expander; linear generator; experimental tests.

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1. Introduction

The air pollutants, the effects of global warming and the depletion of fossil fuels have made the governments, industries, and researchers search new strategies and methods to utilize low grade and wasted heat generating electrical power and achieving higher energy utilization efficiency. There have been increasing attention in unconventional engine configurations not only within academia but also within industries. It is well-known that the internal combustion engine has been invention and commercialization more than a century. Traditional small internal combustion engine systems show many drawbacks including limited operational optimization possibilities, low efficiency and low power-to-weight ratio. The free-piston engine is a linear, 'crank less' internal combustion engine, and its main advantages are simple mechanical structure making the engine compact, low frictional losses, high thermal efficiency with the two-stroke free-piston engine, and operational flexibility [1-4]. Therefore, the free-piston engines as an alternative to conventional engines have invoked the attention in hydraulic and electric power generation applications in recent years [5-11].

Meanwhile, a huge amount of thermal energy is being rejected into the surrounding environment in the form of waste heat, e.g. energy rejected from internal combustion engines, gas turbines and industries (e.g. thermal power plants) through exhaust gases and cooling systems. Many strategies and methods have been adopted to reduce the energy waste and improve the fuel efficiency. Organic Rankine Cycle (ORC) is one of the widely used technologies in low grade heat recovery [12-16]. As a core component of the ORC system, expander has been reported to show significant influence to the overall system performance. In the past decades, research on the expanders has received much attention [17-19].

1.1 Free-piston engine

Since the free-piston engine concept was first presented by Pescara, successful application of free-piston engine concepts of free-piston air compressors, free-piston gas generators during the mid-20th century [1, 20]. Now there have been many different free-piston engines are investigated by numerous research groups due to the potential advantages in terms of high fuel efficiency and low engine emissions. For modern applications, the free-piston engine concept has been proposed for applying as hydraulic free-piston engines aiming for smaller scale applications, free-piston engine generator that aims for application in hybrid electric vehicles, and two-stroke high-speed free-piston diesel engine concept aims for marine application [21-26].

Many theoretical simulation and experimental investigations on the FPE have been done, for the purpose of model-based analysis and control design. Mikalsen and Roskilly have presented a comprehensive overview of the free-piston engine concept from its original design to the other different piston configurations, and summarized the recent applications coupled with the free-piston engine [1]. For all types of free-piston engines, the main challenge for such engine type is the control of the piston motion, which has not yet been fully resolved. Johansen *et al*. presented a dynamic mathematical model of a free-piston diesel engine, and provided a detailed investigation on the piston motion control structure along with its dynamic analysis based on the proposed piston motion control system [27, 28]. Mikalsen *et al.* investigated the basic control strategies of a single piston free-piston engine using a full-cycle simulation model, and studied the piston motion control method and engine dynamics using a decentralized PID controller, and a PDF controller with the disturbance feedforwarded. They also presented a predictive piston motion control strategy to improve the engine dynamic performance and reduce the control delay [29-31]. Zuo *et al.* analyzed the engine scavenging using multi-dimensional numerical model to evaluate the scavenging performance for a free-piston linear alternator (FPLA) [32]. Zhao investigated the cycle-to-cycle variations in the piston dynamics and cycle stability of hydraulic free-piston engines (HFPEs) based on the experimental study of a prototype of the single-piston HFPE [5, 33].

1.2 Free-piston Expander

According to the literatures, there are two main types of expanders in application of ORC system, *i.e.* velocity type includes axial turbines and radial-flow turbines; and positive displacement type includes screw expanders, scroll expanders, piston expanders with crankshaft, and rotary vane expanders [34]. Turbine expanders are reported to be widely used in large scale power systems with the output of 50 kW and above. For small scale units, the positive displacement expanders are preferred [17, 34]. The selection and design of expander is of significant influence to the system efficiency of ORC system.

Free-piston expander was first developed by researchers at Technical University Dresden in the 1990s [35]. Compared with the other expander concepts, the free-piston expander was reported to be one of the most suitable expander concepts due to its potential advantages of good sealing, low frictional loss, and simple structure with a promising efficiency of up to 50% [36, 37].

Researchers at Xi'an Jiaotong University presented a design and experimental validation of a double acting free-piston expander [38]. A slider based inlet/outlet control strategy was applied to realize a full expansion process for the expander. The expander prototype worked stably in a wide range of pressure differences, with an isentropic efficiency of 62% calculated from the p-V diagram analysis [38]. B.S. Preetham *et al.* investigated the operation of a small scale free-piston expander that operated using low temperature waste heat sources to produce power output [39]. The design was based on a sliding-piston architecture, operating parameters such as piston mass, external load, and heat input were varied to identify conditions to achieve optimal performance. The simulation results indicated that the p-V diagram resembled a constant pressure cycle for certain sets of operating conditions [39]. By increasing the heat input to the system, the engine operating frequency was reduced, while the power output increased. C. Champagne *et al.* presented initial experimental analysis of a small scale free-piston expander, and examined the operating conditions to improve the system operational performance [40]. Optimized variables included the piston length and mass, expander size, input pressure, as well as engine lubrication. Results indicated that thick lubricants sealed well in static configurations, and piston speed was decreased during the testing process [40].

It is found that the research outcomes are mostly on the mechanical performance of the engines/expanders and no results showing the performance/output of the electric generator driven by the free-piston linear expander (FPLE).

1.3 Aims and methodologies

The purpose of this research is to study an air-driven free-piton linear expander (FPLE) coupling with a linear electric generator, to find out the relation between the system operation characteristics with the piston movement. This study is also based on the previous simulation studies of FPE model-based analysis by Mikalsen and Roskilly. A prototype of the FPLE with a linear electric generator has been developed by the authors' group. Compared with the conventional expanders, this FPLE configuration shows significant benefits, such as compact design, low friction loss, high efficiency and good operational flexibility. The performances and fundamental principles of the FPLE will be investigated and analyzed with experimental data. The tested piston motion profiles, such as piston displacement, output voltage from the linear generator, and frequency variation of piston motion with different driven pressures will be studied and analyzed. It aims to identify the potential advantages of the FPLE through continuous operation. This research provides a guidance for the establishment and development of the FPLE with a particular focus on applications to utilise of low grade heat for electric power generation.

2. Air-driven free-piston linear expander system

2.1 Configuration

As described in a reviews paper by Mikalsen, there are three types of free-piston engines with different piston configurations [1]. Considering dual structure has the compact structure and higher power/weight ratio, the free-piston with double-piston structure is designed as shown in Figure 1. It is consisted of two parts, *i.e.* the free-piston linear expander (FPLE) which contains dual-opposed pistons and two cylinders, connected by a connecting rod, and the linear generator with rows of permanent magnet installed on the connecting rod and the coils arranged in the stator. The linear generator is fixed to the FPLE to produce electric power. Two opposing pistons move back and forth to generate electricity during the expansion process. The intake valves control the driven air pressure and flow, and the electro-magnetic valves manage the exhaust ports. The opening/closing of the electro-magnetic valves is controlled by the FPLE control system.

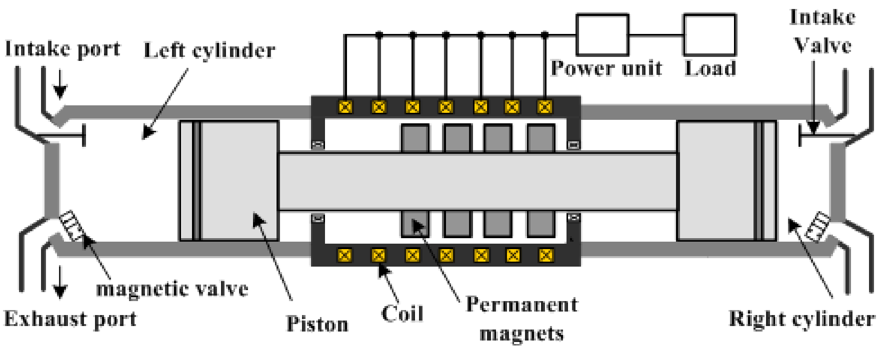

Figure 1. Structure of free-piston linear expander

2.2 Experimental test rig

The designed FPLE system is shown in Figure 2. The two free-piston expanders and the linear generator are fixed with a connect rod. The bore of the expander is 39.0 mm, and the stroke is variable. Sensors and actuators are used to electronically control the movement of FPLE. The piston displacement sensor and the cylinder pressure sensor are used to measure the parameters of the expander dynamics, the expansion process, and provide the signals to the controller. The incremental magnetic sensor is used for measuring the position/displacement from one side to another. The intake air pressure is determined by the pressure sensor. On the basis of these signals, the controller was able to control the operation of the free piston via calculating control parameters. The National Instruments (NI) data acquisition is used to realize data logger for many parameters, such as pressure, displacement and the output voltage.

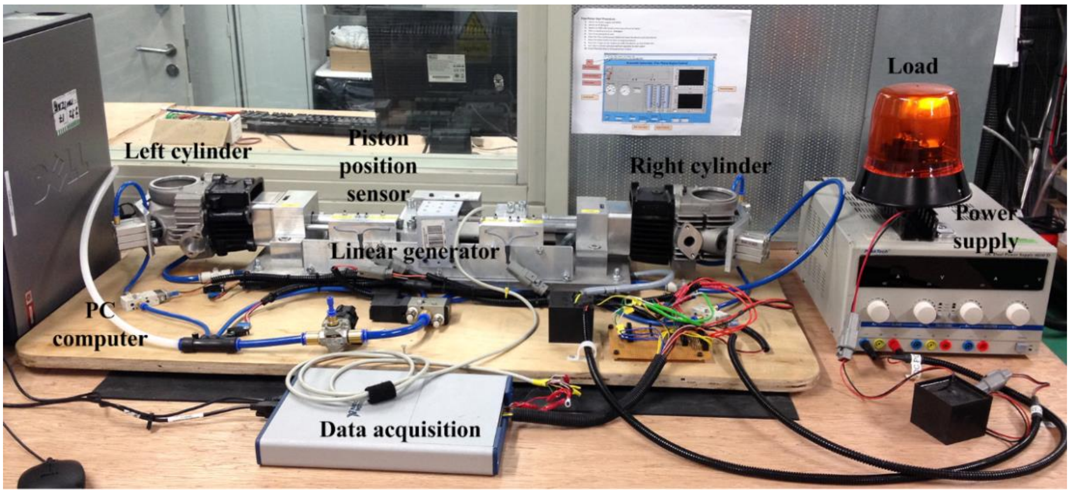

Figure 2. Free-piston linear generate prototype

The working process can be briefly described as follows (see Figure 1 and 2). When the system is initialised, the intake port (valve) of the piston on the left side is opened; the compressed air from an air storage unit flows into the left cylinder; the piston is then driven by the compressed air and moving from its Top Dead Center (TDC), towards its Bottom Dead Center (BDC), *i.e.* from the left to the right until it completes the expansion process. Then the exhaust port is opened. At this moment, the piston on the right side is at its TDC and the intake port is opened, and the compressed air is supplied from the air storage unit to the right cylinder through its intake port, driving the piston on the right side towards its BDC on the left until completing the second expansion process, while the air in the left cylinder is driven out by the left cylinder. Then the working processes restart again. Compressed air is used as the driving energy source for the expansion process for each cylinder, which drives the piston assembly move back and forth. The linear generator converts parts of the mechanical energy into electricity, which will be consumed by an external load.

2.2 Data acquisition and control system

The data acquisition and control system for the FPLE is illustrated in Figure 3. The LabVIEW software is used as the development environment for the display and monitor of the real time signals. The National Instruments (NI) X6341 is adopted as the multi I/O acquisition system to collect data from the sensors, and the board is equipped with analog and digital inputs and outputs. The mainly tested signals include the piston displacement, piston Top Dead Center (TDC), cylinder pressure, and the output voltage of the generator. The tested piston displacement is used as a feedback signal to control the opening/closing of the intake/exhaust ports (valves).

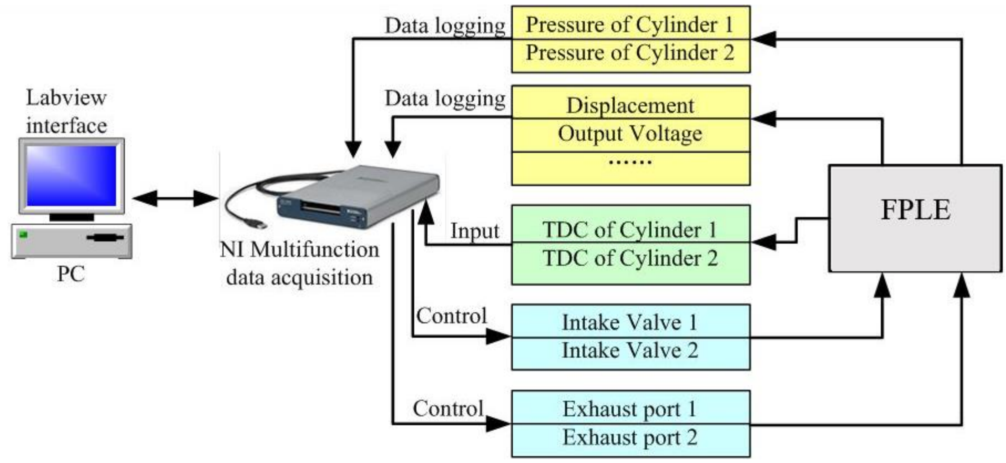

Figure 3. Data acquisition and control system

3. Experimental Results and discussions

3.1 Piston dynamics

During the operations, the control variables of FPLE were fixed, and remained unchanged during the testing. The position profile of prototype was measured, and the piston velocity was calculated based on it. Note, the speed/velocity is obtained as a derivation of the position thus there is also some inaccuracy. When the system is initialized, the intake port (valve) of the piston on the left side is opened, the compressed air from an air storage unit flows into the left cylinder. The initial in-cylinder pressure for both cylinders could be different from that during the steady operation condition at the same piston position. As a result, the piston amplitudes of the first cycles vary from that during the steady operation condition. The experimental data is collected from 1s after the system is initialized, when the piston amplitude is stable. The possible errors could be the sensitivity error of the pressure sensors and the piston displacement sensor, which are controlled within 2% according to the manuals. Meanwhile, the testing is undertaken at ambient pressure in the lab, which may vary and cause errors for the data.

The piston displacement and the corresponding velocity with a driven pressure of 3 bar for two consecutive operation cycles are shown in Figure 4. It is observed that the piston displacement profile is similar with a sinusoidal wave, and the stroke is approximately 60 mm. The peak velocity is usually achieved when the piston approaches the middle stroke. At the dead centers, the piston slows down significantly due to the force from the compressed air. According to the relationship function of displacement, velocity and acceleration, the piston acceleration can be calculated. Then the inertial force acts on the piston can be then acquired with the equation $F = ma$, and the result is show in Figure 5.

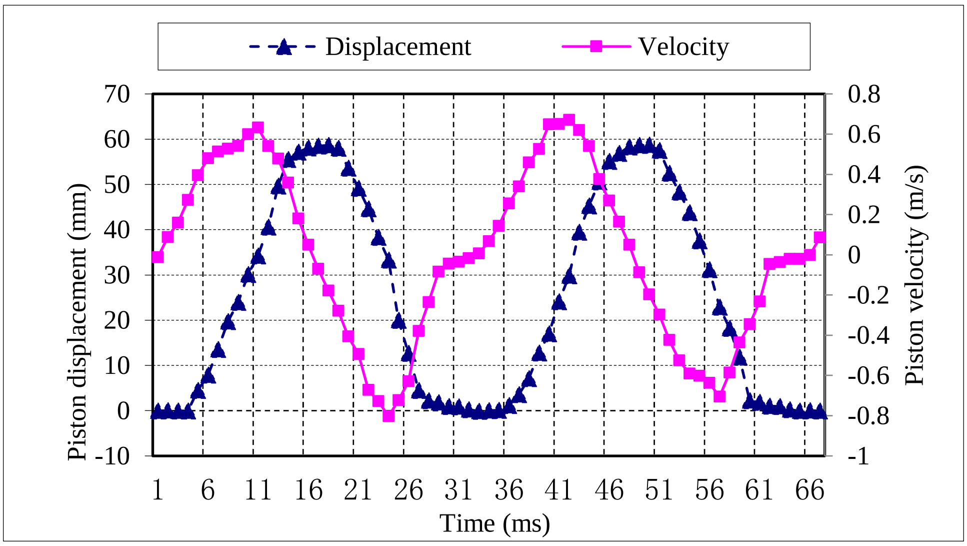

Figure 4. Piston displacement and velocity with a driven pressure of 3 bar

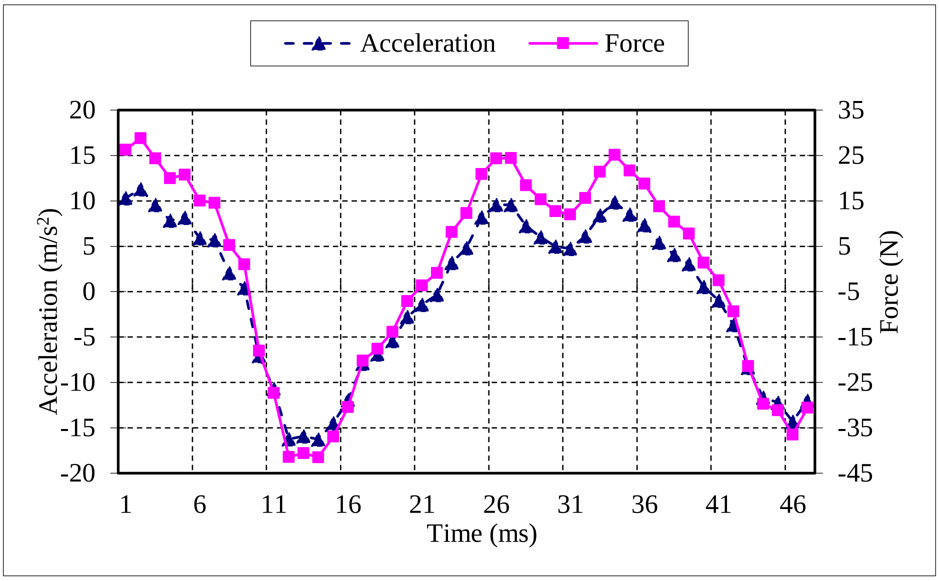

Figure 5. Inertial force and acceleration with the driven pressure of 3bar

The data in Figure 6 shows the free-piston speed vs piston position during the steady operation condition. The piston is found to run at relative high speed during the middle stroke, and then increase/decrease quickly around the dead centers. High cycle-to-cycle variations on the piston velocity can be observed. With all the operation parameters remain unchanged, the peak velocity varies from 0.7 m/s to 0.9 m/s. However, the piston TDC remains almost the same. The profile is similar with an ellipse despite the variations, and the changing trend shows similar trends with the simulation and experimental results in Ref. [23] and Ref. [3], indicating that the designed test can represent the fundamental operation characterizes of the free-piston linear expander.

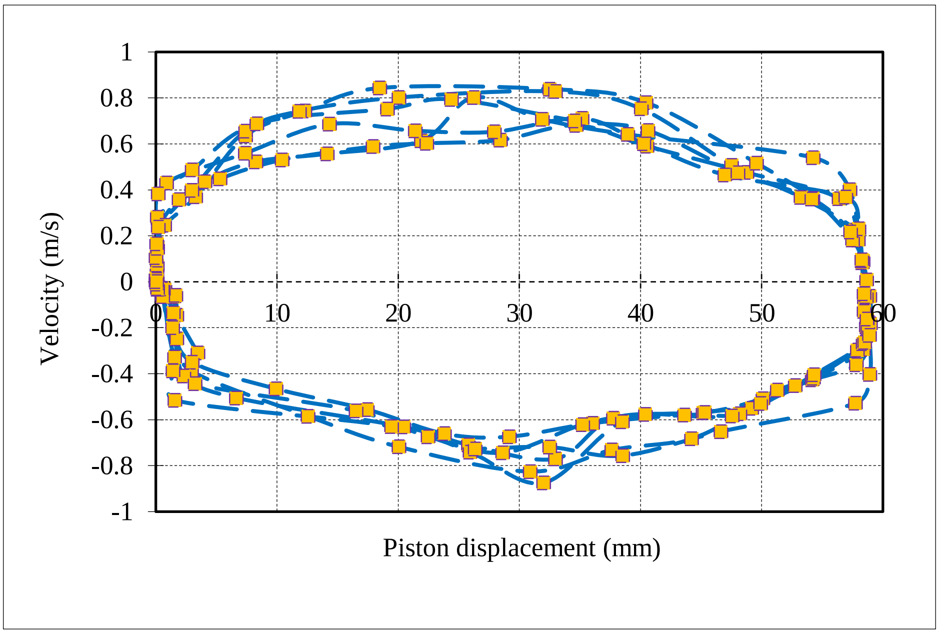

Figure 6. Piston velocity vs displacement with a driven pressure of 3.25 bar

3.2. Output voltage

The data in Figure 7 shows the output voltage of the generator with different driven pressures from 2.0 bar to 3.75 bar. The output voltage stays at a stable state during the middle stroke, and then changes quickly around the dead centers. It is observed that the changing trend of the output voltage is similar with that of the piston velocity shown in Figure 6, indicating that the output voltage is sensitive with the piston velocity. Moreover, with the driven pressure of less than 3 bar, a more stable voltage can be generated.

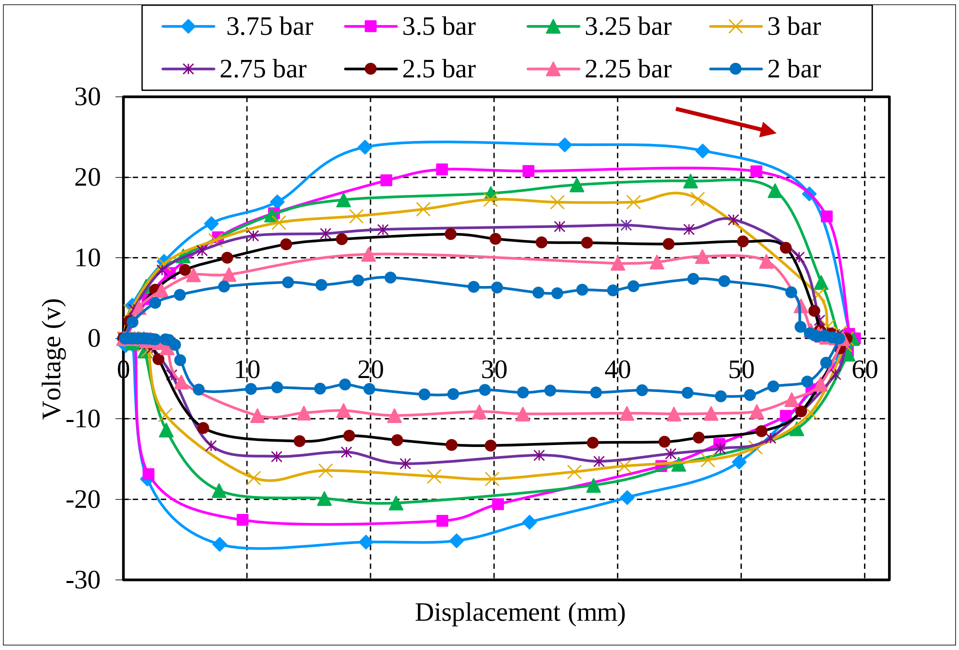

Figure 7. Output voltage vs piston displacement

The peak output voltage vs the driven pressure is collected and demonstrated in Figure 8. With higher driven pressure, the peak output voltage from the generator is found to be higher, and shows a linear relation to the driven pressure value. Thus a linear regression was undertaken, and then the relation between the peak output voltage and the driven pressure is linearized and expressed by: $V = 7.031p - 8.7009$. Where V represents the peak output voltage, and p is the driven pressure. With this linearized equation, given by the peak output voltage, the required value for the driven pressure can be easily calculated.

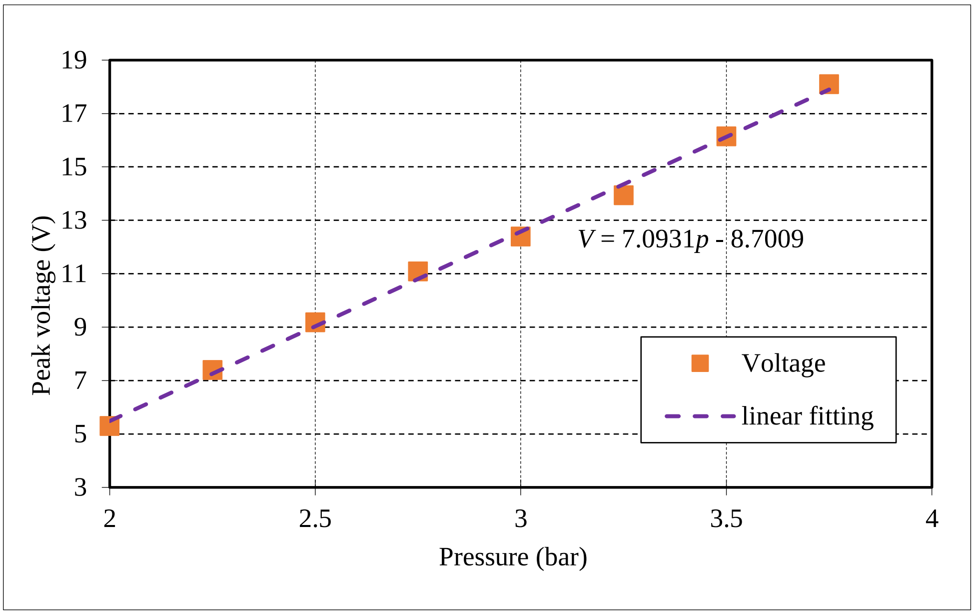

Figure 8. Peak output voltage with different driven pressures

3.3 Operation frequency

In order to get further understanding of the relation between the driven pressure adopted and the piston motion characteristics, the FPLE operation frequency with different driven pressures was calculated and shown in Figure 9. It is seen from the figure that, with higher driven pressure, the FPLE frequency is higher. With the driven pressure, p increases from 2 bar to 2.75 bar, the FPLE operation frequency, f increases correspondingly from 1.5 Hz to 3 Hz, and the increasing rate $\Delta f/\Delta p$ is approximately 2. While when the driven pressure increases from 3 bar to 3.75 bar, the corresponding FPLE operation frequency increases from 3.25 Hz to 3.75 Hz, and $\Delta f/\Delta p$ drops to less than 1. With the increase of the in-cylinder pressure, more energy will be consumed by the frictional loss, the heat transfer from the in-cylinder gas to the cylinder liner, and the gas leakage through the piston rings [3, 23]. As a result, the relation between the driven pressure and the system operation frequency is nonlinear, and the FPLE operation frequency is more sensitive with the driven pressure when a relative low pressure is used. When the driven pressure reaches a certain level (3 bar in this research), the influence of the pressure level to the expander operation frequency is reduced.

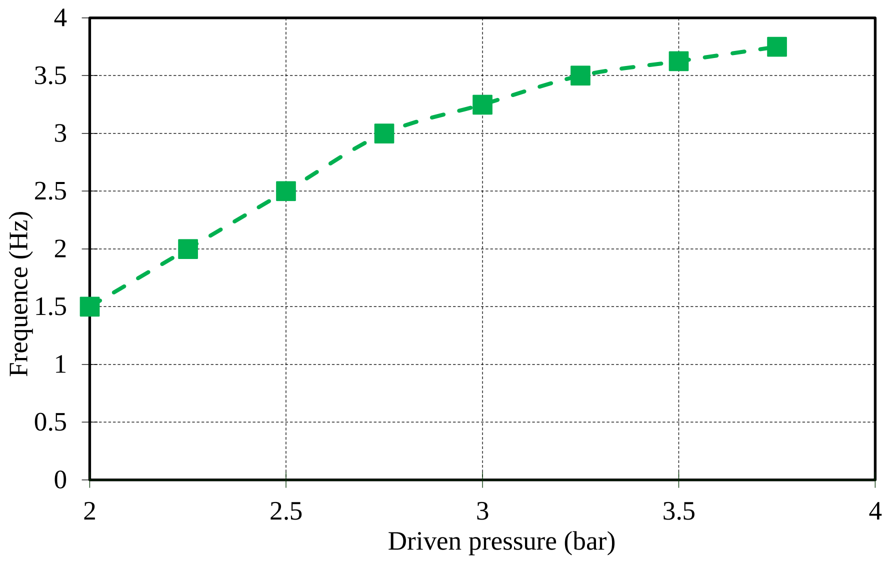

Figure 9. FPLE operation frequency with different driven pressures

4.3. System energy conversion efficiency

It is well known that the free-piston engines have potential higher efficiency compared with conventional reciprocating engines. In this research, the system energy conversion efficiency of the FPLE system, η is calculated with different driven pressures. The system energy input is calculated by the driven pressure of the intake air p_{in}, the piston area A, and the piston stroke S. The electric power output is calculated by the output voltage U, output current I, and operation duration t. The calculation process is illustration in Figure 10.

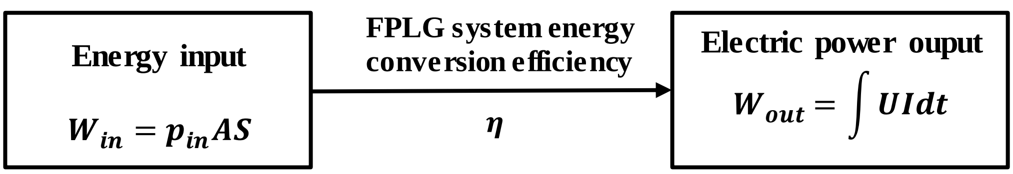

Figure 10. FPLG system energy conversion efficiency calculation

The system energy conversion efficiency vs the driven pressure is shown in Figure 11, with the peak piston velocity compared in the same figure. The conversion efficiency is 23% with a driven pressure of 2.0 bar and it increases with higher driven pressure. The system energy conversion efficiency can reach up to 40% with a driven pressure of 3.0 bar, and 55% with a driven pressure of 3.75 bar. The peak piston velocity shows linear relation with the driven pressure. With the pressure varies from 2 bar to 3.75 bar, the peak piston velocity increases from 0.4 m/s to 0.9 m/s.

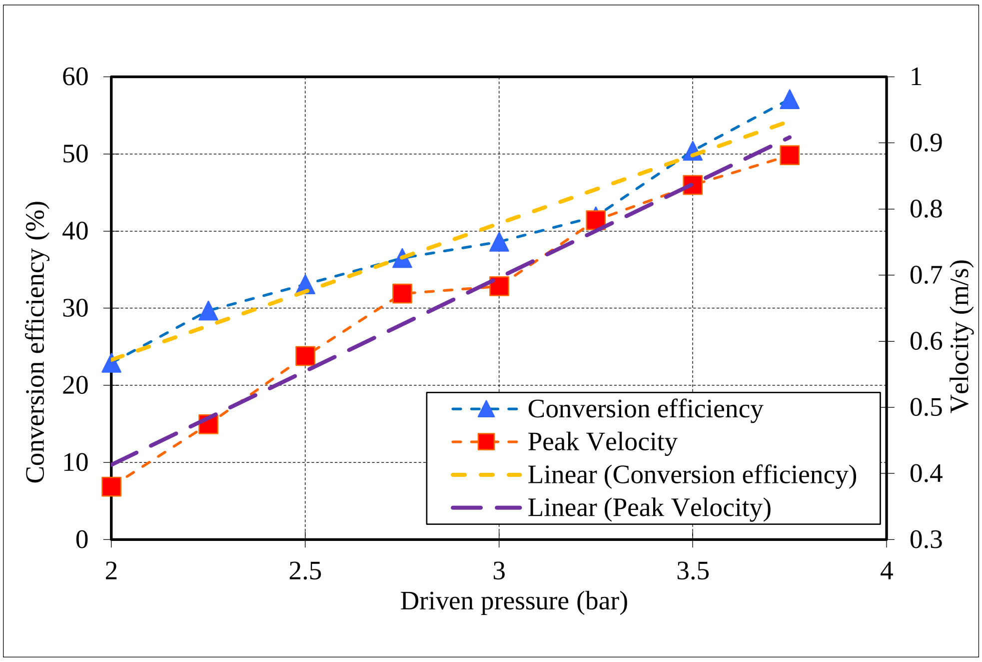

Figure 11. FPLG system energy conversion efficiency and peak velocity vs intake pressure

4. Conclusions

In this research, an experimental study of an air-driven free-piton linear expander (FPLE) is presented, and the relation between the system operation characteristics is provided. The piston motion characteristics, the output voltage, and the expander operation frequency, as well as the system energy conversion efficiency are identified. It is observed that the piston displacement profile is similar with a sinusoidal wave. The piston is found to run at relative high speed during the middle stroke, and peak velocity is usually achieved when the piston approaches the middle stroke. High cycle-to-cycle variations on the piston velocity can be observed. The changing trend of the output voltage is similar with that of the piston velocity, indicating that the output voltage is sensitive with the piston velocity. With higher driven pressure, the expander frequency is higher and the expander operation frequency is more sensitive with the driven pressure when a relative low pressure is used. The energy conversion efficiency increases with higher driven pressure and can reach up to 55% with a driven pressure of 3.75 bar.

The experimental method and results presented in the article provides a guidance for the establishment and development of the FPLE for range-extended applications. Compared with the other expander concepts, it can be found that the system efficiency of the FPLG coupled with a linear electric generator is improved. Along with its advantages of low frictional loss, compact structure, etc. make it a promising expander system for utilisation of low grade heat for electric power generation.

Acknowledgement

This project is supported by the EPSRC through Grants of 'LH Cogen: Low grade heat driven adsorption-linear-expander cycle for cogeneration of power and refrigeration (EP/I027904/1)' and 'GLOBAL - Sustainable Energy through China-UK Research Engagement (SECURE, EP/K004689/1) '. We would like to thank the sponsor.

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